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Pup Production at Scotian Shelf Grey Seal (*Halichoerus grypus*) Colonies in 2010

Production de nouveaux-nés dans les colonies de phoques gris (*Halichoerus grypus*) du plateau néo-écossais en 2010

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ABSTRACT

We conducted a digital-photographic aerial survey on Sable Island and Hay Island, Nova Scotia and along the coast of Nova Scotia and the outer Bay of Fundy in January 2010 to estimate grey seal (*Halichoerus grypus)* pup production. A total of 57,504 pups was counted on the digital imagery from Sable Island. Given the high quality of the imagery, no correction for missed pups was necessary after analysis of ground-truthing plots. Correction for proportion of pups that died prior to the survey (0.0279) and the proportion of pups born before the survey (0.961 East colony, 0.931 West colony), estimated total pup production was 62,100 with 95% confidence limits of 60,900 to 63,200. The 2010 estimate indicates that pup production on Sable Island has continued to increase, but that the rate of increase has declined over the past two successive surveys. We estimated that 89.5% of pups had been born by the time of the Hay Island survey. Correcting for the proportion born, the estimated number of pups born on Hay Island was 2,492 with 95% confidence limits of 2,240 to 2,770. This is similar to the uncorrected pup count in 2007 (2,616), suggesting that this colony may have reached carrying capacity. A total of 417 pups was counted on four small islands in the vicinity of Seal Island, southwest Nova Scotia. The breeding colony in southwest Nova Scotia has increased since 2007 (pup count 207) and expanded to two adjacent Islands. In 2010, about 50 pups were born at other coastal Nova Scotian colonies; most of these were born on several islands off the eastern shore of Nova Scotia (White Islands 49, Bowen's Ledge 1). The 2007 total in Bowen's Ledge and White Islands was 113.

RÉSUMÉ

Nous avons effectué en janvier 2010 un relevé aérien par photos numériques à l'île de Sable et à l'île Hay, en Nouvelle-Écosse, ainsi que le long de la côte néo-écossaise et dans l'avant-baie de Fundy pour estimer la production de nouveaux-nés du phoque gris (*Halichoerus grypus)*. En tout, 57 504 petits ont été recensés sur les photos numériques prises à l'île de Sable. Vu la grande qualité de ces photos, aucune correction pour omissions dans le dénombrement ne s'est avérée nécessaire après analyse des données sur les parcelles vérifiées au sol. La correction visant à tenir compte de la proportion de petits morts avant le relevé (0,0279) et de celle des petits nés avant le relevé (0,961 pour la colonie de l'est et 0,931 pour la colonie de l'ouest) a mené à une production totale de nouveaux-nés estimée à 62 100, les limites de l'intervalle de confiance de 95 % étant de 60 900-63 200. Il ressort de l'estimation de 2010 que la production de bébés phoques à l'île de Sable a continué d'augmenter, mais à un rythme qui a diminué sur les deux derniers relevés. On a estimé que 89,5 % des naissances avaient déjà eu lieu lors du relevé à l'île Hay. Après correction en fonction de la proportion de naissances, le nombre de petits nés à l'île Hay a été estimé à 2 492, les limites de l'intervalle de confiance de 95 % étant de 2 240-2 270. Cela correspond au nombre (brut) de nouveaux-nés recensé en 2007 (2 616), ce qui laisse croire que cette colonie a peut-être atteint sa capacité biotique. En tout, 417 petits ont été recensés dans quatre petites îles alentour de l'île Seal, dans le sud-ouest de la Nouvelle-Écosse (S.-O.N.-É.). La colonie de reproducteurs du S.-O.N.-É. a augmenté depuis 2007 (207 petits recensés) et s'est étendue à deux îles adjacentes. En 2010, il y eu environ 50 naissances dans d'autres colonies côtières de la province, la plupart dans plusieurs îles du large de la côte Est (îles White 49, Bowen's Ledge 1). En 2007, 113 petits au total étaient nés sur Bowen's Ledge et les îlesWhite.

INTRODUCTION

Regulation through resources must be the basic rule in the absence of predators (parasites), and therefore must apply to top predators (Sinclair et al. 2003). Pinnipeds are upper trophic-level predators, but they do have predators themselves. Killer whales and several of the large sharks species are known predators, and predation rates can occur at levels affecting population dynamics. Thus, the relative influence of top-down versus bottom-up regulation of pinnipeds is often not clear. Furthermore, there are few pinniped populations with time series of population estimates that are sufficiently long to illustrate long-term dynamics.

One of the longest series of estimates of pup production comes from a study which began in 1962 at Sable Island, Nova Scotia. The number of grey seal (*Halichoerus grypus*) pups born at Sable Island has increased exponentially for the past four decades (Bowen et al. 2003). The grey seal is a generalist predator feeding on a wide range of demersal and small pelagic fishes (Bowen and Harrison 1994; Beck et al. 2007) in continental shelf ecosystems and inland seas on both sides of the North Atlantic Ocean. Within its Canadian range, the grey seal forages widely throughout the Scotian Shelf and the Gulf of St. Lawrence during the non-breeding season (Stobo et al 1990; Bowen et al. 2006). Major grey seal breeding colonies are located on the sea ice in the southern Gulf of St. Lawrence and on Sable Island, Nova Scotia. Smaller colonies are found on near-shore islands off Cape Breton and along the Eastern Shore of Nova Scotia (Mansfield and Beck 1977; Hammill et al. 1998).

Here we report on the 2010 aerial photographic surveys of grey seal pup production at Sable Island and coastal Nova Scotian colonies, including the largest Hay Island. Our objective was to test the hypothesis that the reduction in the rate of increase in grey seal production at Sable Island had continued and to add to the time series of coastal estimates to obtain an overall estimate of production on the Scotian Shelf. Using long-term life history data from individually marked females at Sable Island, we also update trends in age of primiparity, a trait which is thought to be a relatively sensitive indicator of density-dependent changes in vital rates (Eberhardt 1977).

METHODS

Pup production was estimated from counts of live pups photographed in an aerial census of the established breeding colonies on Hay and Sable Islands. Pup production in Southwest Nova Scotia and Grand Manan, New Brunswick was estimated from visual and photographic counts at colonies located during a coast-wide helicopter survey.

SABLE AND HAY ISLANDS

Digital Photographic Censuses

The digital photographic (RGB 16 bit digital files) censuses of Sable and Hay islands were completed from an altitude of approximately 450 m and approximately 420 m, respectively, using a Microsoft Vexcel UCX camera in Motion compensation camera housing. The camera was integrated with in-flight GPS. Complete coverage of Sable and Hay islands was achieved by flying a series of parallel transects with forward and lateral overlap among adjacent photographs. Each island was photographed during one sortie to minimize double counting of pups due to movement among transects. To obtain more precise geo-referencing for the Sable Island survey (i.e., better than 3 cm ground resolution), a differential GPS base station operated simultaneously with the census on Sable Island.

Photographs of Sable Island were ortho-rectified using a digital elevation model (0.5 to < 0.1 m resolution) based on a LIDAR survey of Sable Island in October of 2009 (David Colville, NSCC). Photographs of Hay Island were ortho-rectified using an elevation model developed from stereoscopic photographs of the island. For each island, one seamless mosaic image was produced from the ortho-rectified photographs using INPHO OrthoMaster software to identify an intelligent seam in a homogeneous area between ortho-photographs. The Sable Island mosaic was then broken into 600 m X 600 m tiles for ease of analysis.

Live pups were counted in ESRI ArcView 9.3. The mosaic tiles were projected in NAD1983-UTM20. A 60m X 60m grid was overlayed on the tiles to facilitate systematic counting. The locations of live pups were marked in a single ArcGIS layer to avoid double counting.

Correction for Missed Pups

The proportion of live pups that were photographed but not detected on the photographs was determined by comparing pups counted in photographed ground plots to the number of pups counted by observers on the ground. In each of six rectangular ground plots the corners were demarcated with red vinyl fabric enabling them to be located on the colour imagery. The plots were widely distributed throughout the east and west colonies and each plot contained > 25 pups. Two researchers on the ground counted pups independently as close as possible to the time the survey aircraft was overhead. Differences between observers were resolved before going to the next plot.

Three readers counted live pups on the aerial photographs of the six ground truth plots independently, and reviewed the counts together to establish a reference count for each ground truth plot. One of the three then read all of the Sable and Hay islands photographs. To correct for directional bias in counting accuracy over time, 30 randomly selected 180 m by 60 m areas (three grid squares) were counted by two readers to establish reference pup counts. Then the original counts were regressed on the reference pup counts. To test for drift in the reader count over time, the difference between the best estimate and the actual count was also regressed with the day on which pups were counted.

Pup Mortality Rate

The proportion of pups that died prior to the aerial census was estimated at eight locations throughout the colony. GPS locations of the vertices of the chosen locations were recorded so they could be plotted on the photographs. The areas chosen encompassed areas of high pup abundance and the polygon boundaries were set in areas of low abundance using natural features such as dune edges, such that the number of pups close to the boundaries was a small proportion of the pups within the boundary. GPS locations were used to create polygons in ArcGIS and the total pup count in the polygon was compared to the dead pups counted and marked. Surveys for dead pups occurred roughly every three days between December 21, 2009, and January 11, 2010.

Temporal Distribution of Births

Temporal distribution of births is estimated from the duration of developmental stages of pups and the temporal shift in the proportion of each developmental stage (Myers and Bowen 1989; Bowen et al. 2007).

To estimate the duration of developmental stages, 54 pups with known birthdates were marked shortly after birth and the stage of each pup was recorded daily until the pup had reached the last stage. Grey seal pups are classified into five developmental stages based on pelage colour and body shape (Radford et al. 1978; Kovacs and Lavigne 1986; Bowen et al. 2003). Here, we use the five stages (Appendix 1) defined by Bowen et al. (2003) and used in previous pup production estimates (Bowen et al. 2007). The mean and variance of the duration (days) for each stage was estimated by fitting a gamma distribution.

To estimate how the proportion in each developmental stage changed over time, we recorded pup stages over the course of the breeding season at nine widely distributed regions (different than the ground plots referred to above) on the island. Seven sites within each region were randomly visited weekly following Bowen et al. (2003, 2007).

We estimated the temporal distribution of births using the method described in Bowen et al. (2007), based on the approach developed by Myers and Bowen (1989). We considered three probability distributions (Gamma, Weibull, and Log-Logistic), to model the number of pups born over time and in all parameterizations, ρ is the scale parameter and κ is the shape parameter. We selected the model with the lowest Akaike's Information Criterion (AIC).

Pup Production Estimates

The estimation of pup production follows the approach given in Bowen et al. (1987), Myers and Bowen (1989) and Bowen et al (2003, 2007). The number of pups born prior to the aerial survey is based on counts of live pups photographed. This number is then corrected for the fractions of live pups not detected on the imagery, pups that had died prior to the survey and hence were not visible on the photographs, and pups that were born after the survey was conducted.

Total pup production was estimated as follows:

$$N_{total} = \sum_{i=1}^{2} \left(\frac{count_i \bullet g}{(1-d) \bullet p_i} \right) \qquad (1)$$

where i = 1 and 2 for the east and west colonies, respectively, and *count* is the count of live pups on the positives, g is the correction for pups missed in the imagery, p is the estimated proportion born prior to the time of the survey in each stratum, and d is the estimated proportion of pups that had died up to the day of the photographic survey. Standard error of total pup production was calculated from the estimated variances of correction factors using the delta method for independent random variables (Goodman 1960, Mood et al. 1974) as follows:

$$\operatorname{var} N_i = N_i^2 \bullet \left(\frac{\operatorname{var} p_i}{p_i^2} + \frac{\operatorname{var} d}{d^2} \right)$$

where i = 1 and 2 for the east and west colony, respectively. Although pups were born over the entire island again in 2007, we retained the separate estimation for the west colony and the east colony because there was clear break in the spatial distribution of pups near the Weather Station at the western end of the Island.

SOUTHWEST NOVA SCOTIA AND GRAND MANAN, NEW BRUNSWICK

Pup production at other colonies was estimated from a helicopter survey. The Nova Scotia coastline between Halifax (44°40'12"N, 63°36'36"W) and Cape St. Marys, Yarmouth County, Nova Scotia (44°05'04"N, 66°12'29"W), and the perimeter of Grand Manan, New Brunswick (44°42'00"N, 66°48'00"W), and surrounding islands were flown in a Bell 206 helicopter (Canadian Coast Guard) on January 30 and 31, 2010. Two experienced observers and the pilot identified four islands with grey seal breeding colonies. Pups were counted in a series of slow passes of each island.

Pup counts were completed at Bowen's Ledge (44°52'6.6"N, 62°09'55.0"W) and nearby White Islands from helicopter by two experienced observers on January 27, 2010.

AGE OF PRIMIPARITY

Recently weaned (i.e., within approximately two weeks) grey seal pups were hot-iron branded with individual marks in 1985, 1986, 1987 and 1989 and again from 1998 through 2002. These branded females provided an opportunity to determine the age at first birth for individuals recruiting to the breeding population on the island. Females observed pregnant or nursing were judged to be primiparous if they had not previously been observed pregnant or nursing. Non-pregnant females are rarely seen among lactating females and fostering is also rare on Sable Island, so we can be reasonably confident that the first year a female was observed she was primiparous.

To determine if a branded female had returned to Sable Island during the breeding season, we conducted weekly censuses of the entire colony. Censuses were conducted by four to eight researchers and the use of all terrain vehicles to ensure that the colony was thoroughly searched. Typically, five or six censuses were conducted each year covering the entire season of births. Although some of the females branded on Sable Island as pups may give birth at other colonies, grey seals exhibit strong philopatry at other colonies, including Sable Island (W. Stobo, unpublished data). Furthermore, Sable Island is by far the largest colony in the Northwest Atlantic and therefore we expected that most females would return to Sable Island to give birth for the first time. Although the number of females giving birth on Sable Island has increased dramatically, in 2007 there was still unoccupied habitat and other areas where the density of females was low such that there is no reason to expect that young females from the 1998 to 2002 cohorts would be excluded from the breeding colony.

Statistical analyses were performed in R version 2.10. The standard error (SE) is given as a measure of variability about means.

RESULTS

SABLE ISLAND

Seventeen transects were flown over Sable island on January 11, 2010, between 12:30 and 14:01 PM (Eastern Standard Time) resulting in 1,179 photographs. Image quality was very high for most of the island, but bright overcast conditions prevailed during portions of the West Colony survey such that imagery was good, but not of the exceptional quality for the rest of the island (Fig. 1). A total of 57,501 pups was counted: 13,002 (22.6%) in the west colony and 44,499 (77.4%) in the east colony (Fig. 2a, Table 5).

A comparison of pup counts by ground observers and those from photographs indicated close correspondence with the greatest difference of about 5% (Table 1). However, in this ground truth plot, the count from the aerial survey may have encompassed a greater area than the count on the ground because the upper edge of the plot counted from the ground was difficult to identify from the aerial photograph. Nevertheless, the mean difference of less than 1% did not differ significantly from zero ($p = 0.58$). Therefore, no correction for missed pups was applied.

We also compared pup counts on reference plots of the imagery compared to counts over time and over a range of pup density to test for bias in the ability of the reader to identify pups. There was no trend in the residuals either over time or with pup density and thus no correction for changes in reader performance were deemed necessary (Fig. 3).

The developmental stage of 54 pups was recorded daily until the pups reached Stage 5 (Appendix 2). Common shape (five parameters) and separate shape (eight parameters) gamma and Weibull models were fit to the transitions of pups from one stage to next. As in 1997 and 2007, the gamma distribution fit the data better than the Weibull distribution. Model results from the gamma distribution are described in Table 2. In 1997 and 2007 the common shape gamma model was not significantly different from the separate shape model, but in 2010 the separate shape is significantly different than the common shape model (change in log likelihood=22.59, χ^2 , df=3, $p<0.001$).

The developmental stage of 9,365 pups was recorded along ground transects in the 13 regions widely distributed throughout the colony over a 47-day period from 17 December 2009 to 22 January 2010 (Appendix 3). Three models were fitted to estimate the distribution of births over time and from that the proportion of pups born by January 11, 2010 (Table 3). Date of the first birth was estimated as December 3rd and December 6th for the east and west colonies, respectively, based on the oldest stage pups (Stage 3) observed on December 12th and 13th. These dates were used to define the limit of the left tail of the modelled distributions. All models fit reasonably well but, based on the AIC criteria, the Weibull model provided the best fit (Table 3).

The eight sites selected to estimate the proportion of pups that had died prior to the census represented 14.0% of the live pups photographed. The mean proportion that had died was 0.028 ± 0.00371 (Table 4).

Estimated N_{total} was 62,100 (rounded to nearest hundred) with 95% confidence limits of 60,900 and 63,200 (based on log-normal distribution) (Table 5). The current estimate of pup production is below the exponential growth curve fit to the data from 1974 to 1994 (Fig. 4). This is the third consecutive survey in which the residuals of the estimated rate of increase are negative, providing support for a further decrease in growth rate (Fig. 5).

HAY ISLAND

Hay Island was surveyed on January 17, 2010, between 13:04 and 13:29 PM resulting in 28 photographs and a total count of 2,168 pups (Fig. 2b, Table 6). To estimate the distribution of births, the developmental stage of 4,164 pups was recorded along four ground transects covering the Island between January 16 and February 4, 2010. Data from Sable Island were used to estimate the duration of each stage and the date of first birth. Three models were fitted to estimate the distribution of births over time and from that the proportion of pups born by January 17th (Table 6). While all three models provide similar estimates of the proportion of pups born prior to the aerial survey, the Weibull model again had the lowest AIC.

No estimates of pre-census pup mortality or correction of missed pups were made for Hay Island. Given that the imagery of Hay Island was of the same high quality as that of Sable Island, no correction for missed pups seemed warranted. Some pre-weaning mortality undoubtedly occurred on Hay Island, so we used the Sable Island estimates to attempt to account for this. Total production was estimated to be 2,490 (rounded) with 95% confidence limits of 2,240 – 2,770 (Table 6).

SOUTHWEST NOVA SCOTIA AND GRAND MANAN, NEW BRUNSWICK

A total of 50 pups were counted from helicopter for breeding colonies on White Island (n=49) and Bowen's Ledge (n=1) (Table 7).

During the helicopter survey of the southwest Nova Scotia and outer Bay of Fundy coastline (Fig. 6), breeding colonies of grey seals were found on only four small islands in the vicinity of Seal Island (43°24'56.1"N, 66°00'37.4"W). A total of 417 pups was counted on these islands (Table 7). There were few mother-pup pairs and most of the pups had been weaned and were in Stage 5 of development. It is likely that all pups had been born at the time of the survey, therefore, no correction for pups yet to be born at the time of the survey was applied.

AGE OF PRIMIPARITY

Compared to the 1985 to 1989 cohorts, females from the 1998 to 2002 cohorts matured consistently later across ages (Table 8). Furthermore, a smaller proportion of females recruited from the recent cohorts compared to the 1980s, suggesting that survival may also be lower.

DISCUSSION

Pup production of grey seals at Sable Island increased exponentially at a rate near r_m for four decades (1962-1997; Bowen et al. 2003). Extrapolating the exponential model (Bowen et al. 2003) using the most accurate series of pup cohorts (i.e., 1976 to 1997) gave a predicted 2004 pup production significant greater than that estimated suggesting that the rate of increase between 1997 and 2004 had declined. Predicted pup production in 2007 from the exponential model is 88,000 compared to the estimated value of 54,500 providing support for a decline in the rate of increase in this component of the grey seal population (Bowen et al. 2007). Results from this study provide evidence of a continued reduction in the rate of increase in pup production and suggest that the population is approaching a resource ceiling (Figs. 4 and 5).

In comparison to the Sable Island breeding colony a relatively small number of grey seals breed on selected islands on the coast of Nova Scotia (Table 7). Historically, culling limited pup production to the low 100s (Mansfield and Beck 1977). While the Basque Islands breeding colony has disappeared as a result of the erosion of these islands, new colonies were discovered on Hay Island in 1993 and Noddy and Flat Islands on the southwestern shore of Nova Scotia (Hammill et al. 2007). The estimated pup count on Hay Island decreased since the last aerial survey in 2007 from 2, 616 to 2, 239 in 2010. During the same time the breeding colonies in southwest Nova Scotia expanded from Noddy and Flat to Round and Mud, two adjacent islands, and increased from 207 in 2007 to 417 in 2010. The increase of several hundred pups in southwestern Nova Scotia must reflect immigration for other colonies. Overall pup production on the eastern coast of Nova Scotia decreased slightly since 2007, because of the decrease in pup production on Hay Island, which may be limited by the area available during the breeding season. Although the time series of estimates from Hay Island is less extensive, the 2010 estimate suggests that pup production at this relatively small island may have

stabilized. Elsewhere along the coast of Nova Scotia relatively few pups are born. Taken as a whole, grey seal production increased between 2007 and 2010, due mainly to the increase on Sable Island.

SOURCES OF ERROR IN ESTIMATED PUP PRODUCTION

Pup counts from the imagery must be corrected for several factors to estimate total pup production. First, as found in previous surveys, some live pups may be missed on the photographs resulting in an underestimate. However, the high quality of the digital images in the present survey made this correction unnecessary. Second, pups that died before the aerial survey was conducted will not have been counted. On Sable Island, drifting sand and snow soon cover dead pups making them invisible on the positives. We corrected for pup mortality and so this should not be a source of bias. We also estimated pup stage durations used to fit the temporal distribution of births model. Model fits to these data were good and thus this should not be a source of error.

TREND IN PUP PRODUCTION

Bowen et al. (2006) noted that a decrease in the rate of increase of pup production on Sable Island could have been caused by density-dependent changes in vital rates or that 2003 could have been a poor year (perhaps low food abundance) such that fewer females gave birth in 2004 resulting in a lower estimate than expected. However, the results from the current aerial survey indicate that the reduction in rate of increase in pup production has continued providing further support for the hypothesis that density-dependence may be limiting the rate of increase.

Pinnipeds have several characteristics that argue for extrinsic rather than intrinsic population regulation (Wolff 1997). Two density-dependent factors which may limit the population are food and space for parturition and pup rearing. Given that unused habitat is still available on Sable Island and along the coast of eastern Canada and northeastern United States, food is more likely to regulate grey seal numbers, consistent with the general view that most large mammals are regulated by food supply (Sinclair 1996). This was suggested by the marked decrease in odds of being primiparous at age 4 yr in recent cohorts compared to those in the 1980s (Bowen et al. 2006) and is further supported by additional data on the proportion recruited at age of recent cohorts compared to those in the mid to late 1980s. Bowen et al. (2006) showed that the number of females giving birth for the first time at ages 4, 5 and 6 differed significantly among cohorts. Expressed as odds ratio, females were about 16 times more likely to give birth for the first time at age 4 during the mid to late 1980s than they were from 1998 to 2000. By contrast, females were more than twice as likely to give birth for the first time at age 6 yr compared to the mid to late 1980s cohorts. The most recent data confirm earlier findings and suggest that in addition to delayed age at first birth, females from the 1998-2002 cohorts also had lower apparent survival.

There are now three consecutive estimates of pup production indicating the exponential growth model is no longer an appropriate description of dynamics (Fig. 5). With these estimates and the recent life history data showing a change in the odds of giving birth for the first time at age 4 yr over five successive cohorts, the case for density-dependent changes is becoming more compelling. Nevertheless, the carrying capacity of the Sable Island component of the population is quite uncertain.

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Table 1. Number of grey seal pups counted on six ground plots and from digital imagery of those plots on January 11, 2010.

Location	Time (PM)		Count (n)		Difference	
	Count	Photo	Ground	Imagery	n	%
Canadian Wildlife Service	1:05	12:30	74	78	4	5.1
West Washover	12:39	1:17	55	54	-1	-1.9
Gully East	12:38	1:30	52	52	0	0.0
East Light Cut	12:49	1:03	87	86	-1	-1.2
BIO 1	1:31	1:30	58	58	0	0.0
BIO 2	1:31	1:40	60	61	1	1.6
Mean (SE)						0.6 (1.02)

Table 2. Estimates of stage durations from daily records pups followed from birth to last stage, data fit with a gamma distribution. 1997 n=47, 2007 n=52, 2010 n=54.

		Common Shape				Separate Shape			
Year	Stage	Shape	Rate	Mean (d)	Variance	Shape	Rate	Mean (d)	Variance
2010	1	21.49	7.68	2.8	0.36	11.18	4.03	2.8	0.69
2007	1	24.95	8.43	3	0.35	30.99	10.42	3	0.29
1997	1	21.2	5.45	3.9	0.71	22.04	5.67	3.9	0.69
2010	2	21.49	5.48	3.9	0.71	88.51	22.52	3.9	0.17
2007	2	24.95	8.2	3	0.37	57.34	18.75	3.1	0.16
1997	2	21.2	5.27	4	0.76	23.44	5.82	4	0.69
2010	3	21.49	1.64	13.1	7.97	31.71	2.42	13.1	5.41
2007	3	24.95	2.09	12	5.73	25.13	2.11	11.9	5.62
1997	3	21.2	2.02	10.5	5.21	19.71	1.88	10.5	5.59
2010	4	21.49	4.75	4.5	0.95	3.72	0.83	4.5	5.45
2007	4	24.95	4.76	5.2	1.1	9.52	1.8	5.3	2.93
1997	4	21.2	3.01	7	2.34	24.29	3.44	7.1	2.05

Table 3. Estimates of the proportion of pups born by January 11, 2010 (Sable Island, East and West) or January 17, 2010, (Hay Island) based on the three models and the date of first birth. Standard error is in parentheses. All models had two parameters.

Colony First birth	Model	Shape	Rate	Proportion Born	AIC
Sable, East Dec 3, 2009	Log-Logistic	3.8155(0.3680)	0.0413(0.0089)	0.8454(0.1057)	6767.36
	Gamma	5.7129(0.7597)	0.2275(0.0352)	0.8979(0.0213)	6796.79
	Weibull	3.0801(0.2081)	26.5846(0.5251)	0.9614(0.0102)	6763.71
Sable, West Dec 6, 2009	Log-Logistic	3.2163(0.2740)	0.0434(0.0021)	0.8073(0.0373)	4428.37
	Gamma	4.3377(0.6190)	0.1795(0.0317)	0.8520(0.8520)	4445.44
	Weibull	2.6958(0.1355)	24.9868(0.6455)	0.9312(0.0127)	4407.01
Hay Island Dec 3, 2009	Log-Logistic	9.0094(0.9080)	0.0283(0.0062)	0.8978(0.0320)	4820.47
	Gamma	25.3731(3.5650)	0.7084(0.1174)	0.8961(0.0346)	4847.12
	Weibull	5.1983(0.5721)	38.4807(1.1491)	0.8952(0.0487)	4815.83

Distribution	Density Function	Number of Parameters
Gamma	$\rho(\rho t)^{\kappa-1}\exp(-\rho t)$	2
Weibull	$\kappa\rho(\rho t)^{\kappa-1}\exp[-(\rho t)^{\kappa}]$	2
Log-Logistic	$\kappa\rho^{\kappa}t^{\kappa-1}[1+(t\rho)^{\kappa}]^{-2}$	2

ρ=scale, κ=shape parameter

Table 4. Percentage of pups that died up to 11 January, 2010, at 8 sites on Sable Island.

Area	Live Pups from Imagery	Dead Pup Count	Percentage
East Light Dune	1109	35	3.16
Legal Crossing	1433	41	2.86
CWS - Tern Colony	496	11	2.22
Blowout	1922	36	1.87
South Beach (to Beck's Cove)	638	33	5.17
No. 4 West	1216	32	2.63
Bald Dune Cove	721	16	2.22
East Light Cut	507	11	2.17
Mean (SE)			2.8 (0.37)

Table 5. Estimate of grey seal pup production on Sable Island in 2010 with SE in parentheses.

	West Colony	East Colony	Sable Total
Pup counts from positives	13,002	44,499	57,501
Proportion born by Jan 11th	0.9312 (0.0132)	0.9600 (0.0104)	
Dead pup correction	0.028 (0.0037)	0.028 (0.0037)	
N_{total}	14,365	47,689	62,054 (587)
95% confidence limits			60,900 – 63,200

Table 6. Estimate of grey seal pup production on Hay Island in 2010 with SE in parentheses.

Hay Island	Estimate
Pup counts from positives	2,168
Proportion born by Jan 17	0.8952 (0.0487)
Dead pup correction	0.028 (0.0037)
N_{total}	2,492 (136)
95% confidence limits	2,239-2,772

Table 7. Total count of pups from aerial survey imagery and helicopter surveys with real time counting.

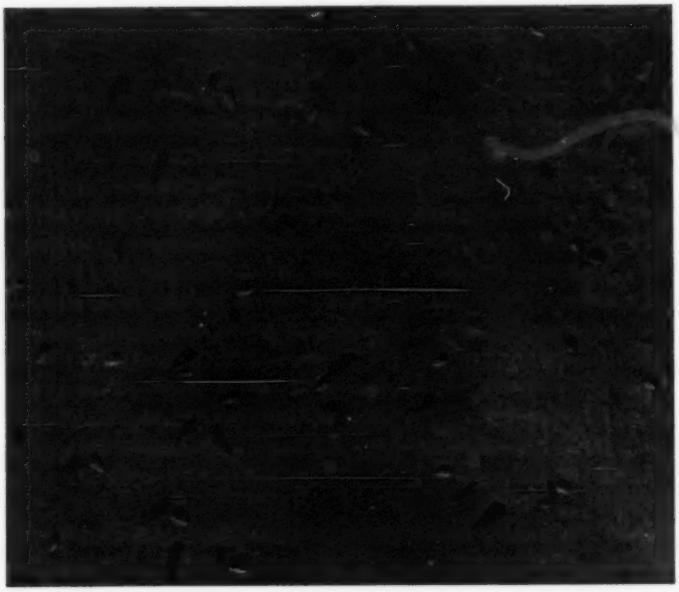
Location	Date	Count Pups	Corrected Estimate Pup Production	SE	Percentage Total
Eastern Shore					
Hay Island	Jan 17	2168	2,492	136	
White Island		49	49		
Bowen's Ledge		1	1		
Total			2,542		
Southwest Shore NS					
Flat Island	Jan 30	85	85		
Mud Island	Jan 30	113	113		
Noddy Island	Jan 30	112	112		
Round Island	Jan 30	107	107		
Total		417	417		
Sable Island	Jan 11	57, 501	62,054	587	
Grand total			65,000[1]		

[1] Rounded to nearest 100.

Table 8. Number of female grey seals branded and the cumulative percent recruited at ages 4 to 10 for cohorts 1985 to 2002.

Cohort	N Branded	Recruited (%) Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10
1985	400	7.5	30.2	47.2	54.2	59.2	60.8	64.5
1986	400	16.8	41.2	51.7	56.0	58.8	61.3	63.2
1987	400	11.8	34.2	48.0	54.8	58.0	64.2	66.8
1989	500	7.6	27.8	38.0	51.6	57.8	61.2	63.6
1998	150	0.0	13.3	22.0	29.3	33.3	35.3	36.0
1999	250	0.0	16.4	29.2	34.4	36.4	38.4	39.2
2000	250	1.2	11.6	20.0	26.0	28.4	28.8	30.8
2001	250	1.2	12.0	18.8	22.8	24.8	25.2	
2002	250	2.8	9.2	19.2	23.6	28.0		

a)



b)

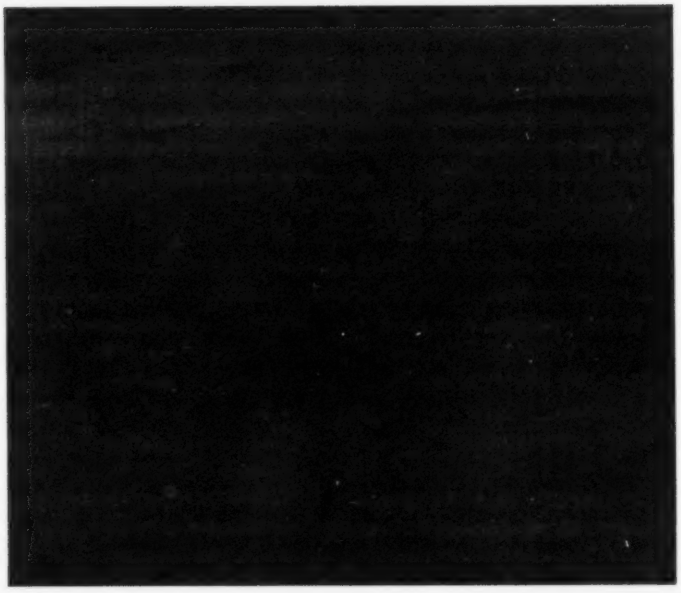
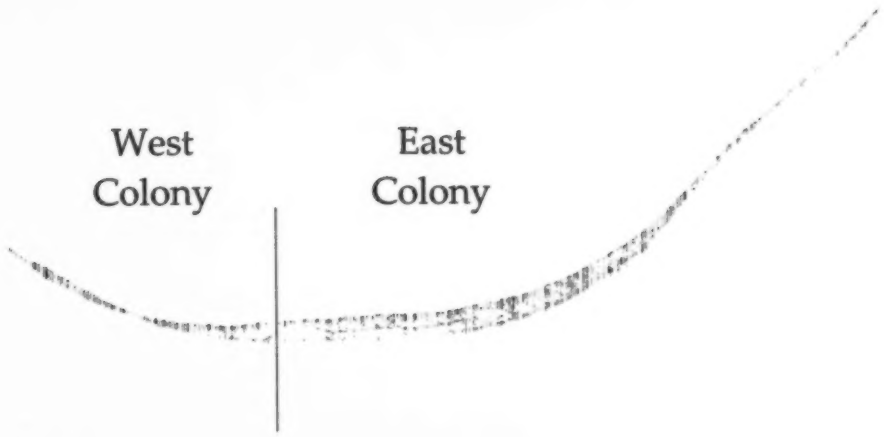


Figure 1. Example of digital imagery from the 2010 survey under clear skies (a) and overcast conditions (b) with live pups counted (pink dots). Scale 1:150.

a)



b)

Figure 2. Distribution of pupping (black dots) on Sable Island (a) (Scale 1:250,000) and on Hay Island (b) (pups indicated with pink dots, Scale 1:2,500) in January 2010.

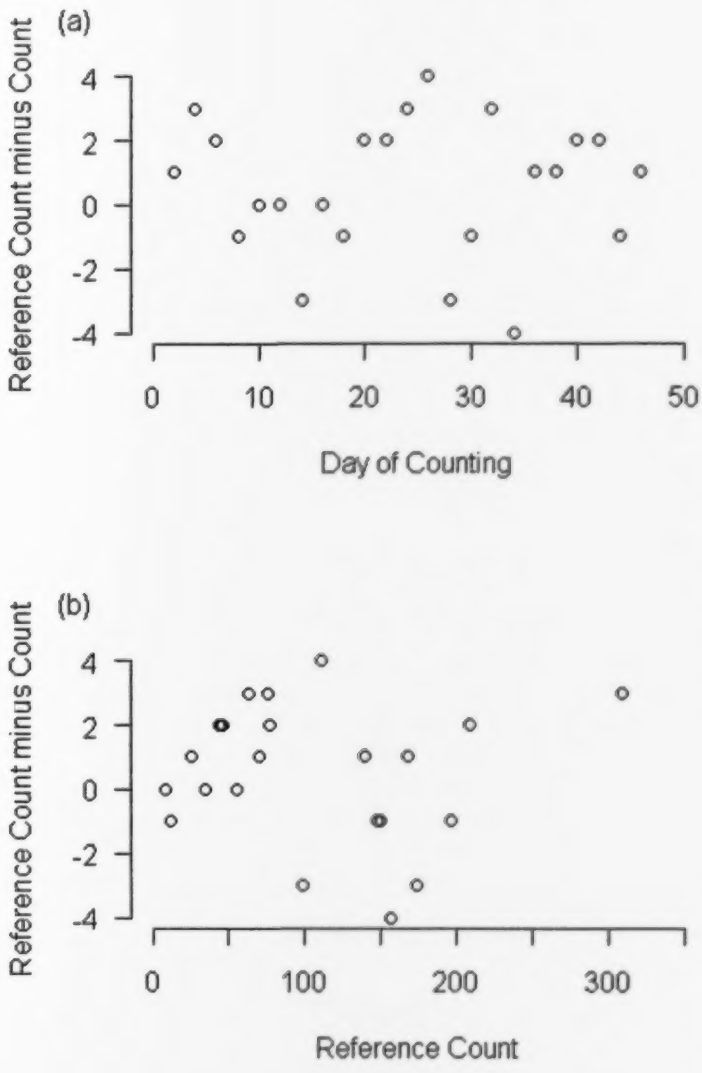


Figure 3. Comparison of the difference between pup counts on reference plots and the actual counts over the duration of the analysis of the digital imagery (a) and over range of pup density (b).

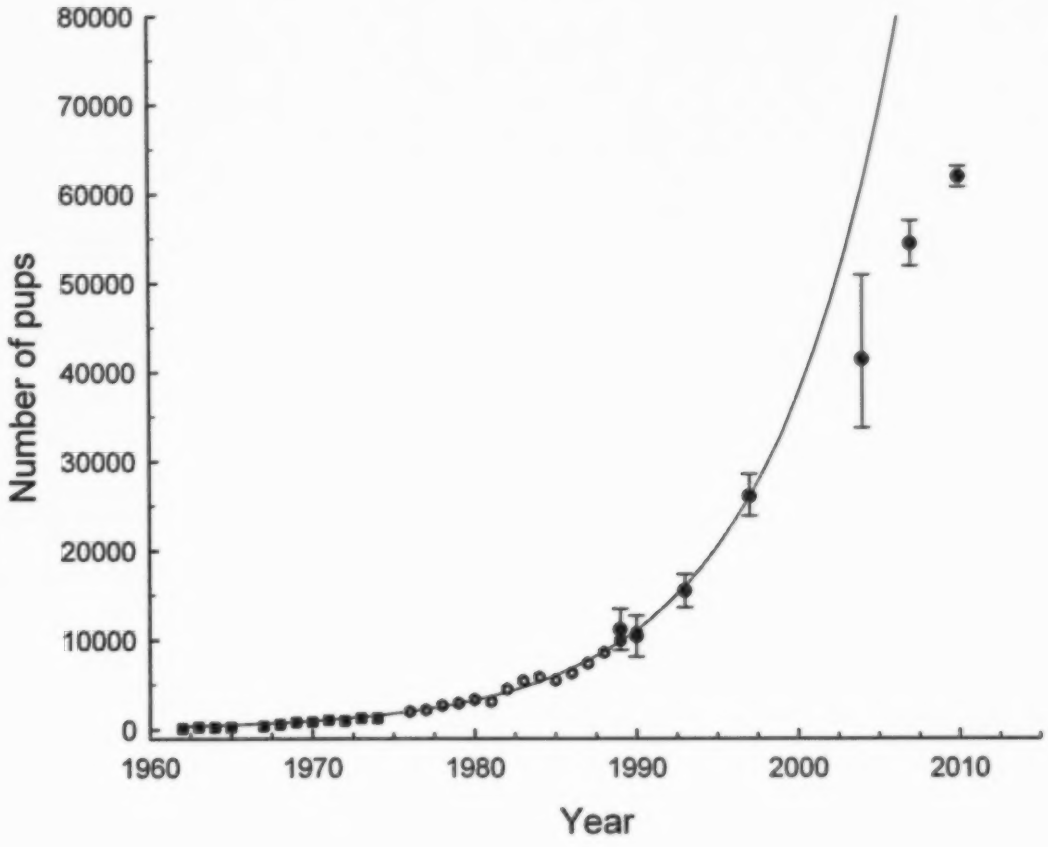


Figure 4. Trend in grey seal pup production on Sable Island, 1962 to 2010, based on incomplete tagging (1962-1974), complete cohort tagging (1976-1990) and aerial photographic surveys (1989-2010). Error bars are approximate 95% confidence limits. Solid line represents an exponential curve fit to the 1976 to 1997 estimates.

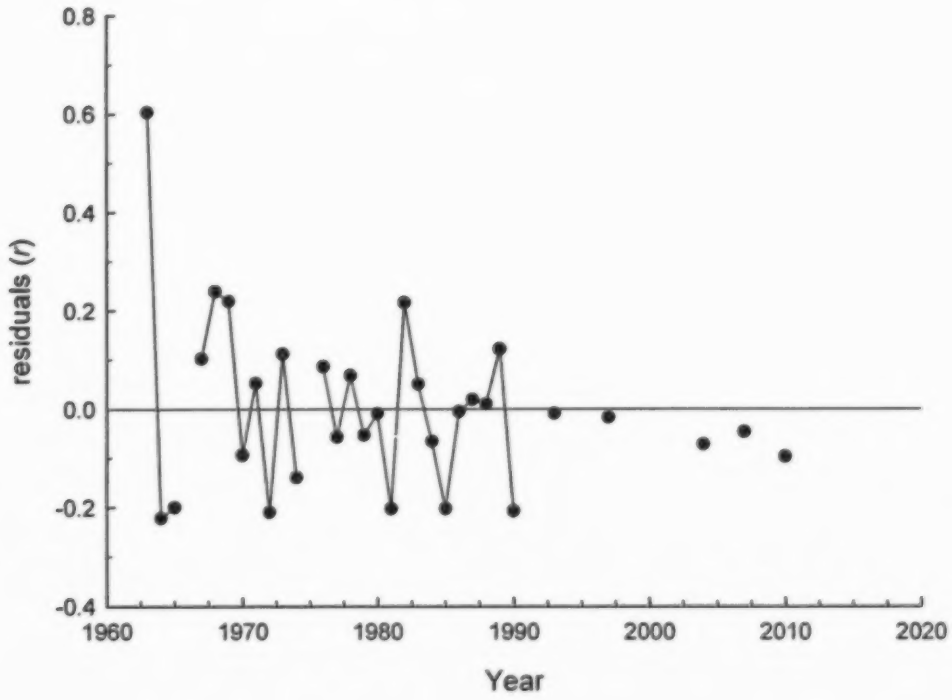


Figure 5. Residual of the instantaneous rate of increase in pup production on Sable Island over time showing negative residuals for the last three surveys.

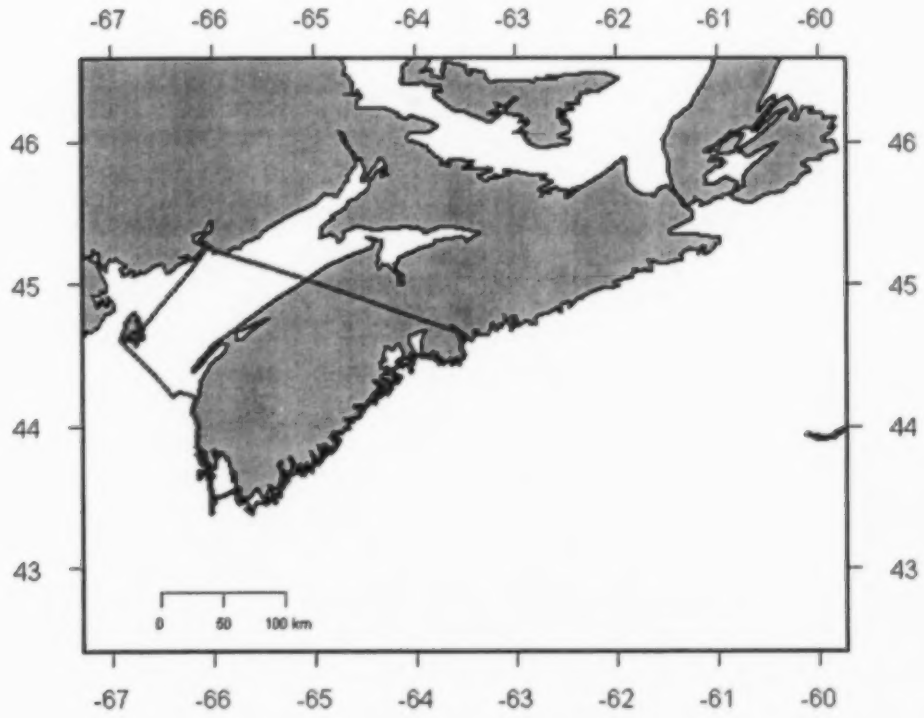


Figure 6. Plot of the reconnaissance flight from Halifax, Nova Scotia to Grand Manan, New Brunswick. The red track was flown on January 30, 2010 and the green track was flown on January 31, 2010.

Appendix 1. Developmental stages for grey seal pups.

Stage	Description
1	pup: new born, wet, weak, yellowish (possibly)
2	pup : tubular shape; gut is not larger than the shoulder
3	pup: gut is larger than the shoulders; no sign of molting
4	pup: molting but < 95% molted
5	Pup: >= 95% moulted

Appendix 2. Developmental stages (1 to 5) at age (days) for grey seal pups followed from birth (Age 0) to Stage 5. 9 indicates the pup stage was not determined.

Tag	Age, Days																														
No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
7601	1	1	9	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	5			
7602	1	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	9	9	9	9	9	9	9	9	9	9	9	9	
7603	1	1	9	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	9	9	
7604	1	1	9	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	9	5			
7605	1	1	9	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	5							
7606	1	1	9	2	2	2	2	3	2	3	3	3	3	3	3	3	4	4	4	5												
7607	1	1	9	2	2	2	2	2	2	3	3	3	3	3	3	3	3	4	4	4	5											
7608	1	1	9	2	2	2	2	3	3	3	3	3	3	3	3	3	4	4	4	4	4	5										
7609	1	1	9	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	5			
7610	1	1	9	2	2	2	3	2	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	5			
7611	1	1	9	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	5							
7612	1	1	9	2	2	2	2	3	3	3	3	3	3	3	3	4	4	4	5													
7613	1	1	9	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	5						
7614	1	1	9	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	5							
7615	1	1	9	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	5					
7616	1	1	9	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	9	9	9	9	
7617	1	1	1	1	1	1	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	9	5	
7618	1	1	9	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	9	9	
7619	1	1	9	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	5								
7620	1	1	9	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	5			
7621	1	1	9	2	2	2	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	5										
7622	1	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	9	9	9	9	9	9	9	9	
7623	1	1	9	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	4	4	5											
7624	1	1	9	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	5							
7704	1	1	1	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	5	
7705	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	5									
7706	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	4	4	5												
7707	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	4	4	5												

Appendix 2. (Continued.)

Tag	Age, Days																														
No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
7708	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	5								
7709	1	1	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	5				
7710	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	9	4	4	4	5							
7711	1	1	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	9	9	4	4	4	5						
7712	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	5								
7713	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	5					
7714	1	1	1	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	5							
7715	1	1	1	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	5			
7716	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	5			
7717	1	1	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	5					
7718	1	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	5							
7719	1	1	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	9	4	4	5							
7720	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	5
7721	1	1	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	4	9	9	9	9	9	9	9	9	9	9	9	9	9
7722	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	9	4	4	4	4	5					
7723	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	5
7724	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	5
7725	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	5						
7726	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	9	9	9	4	4	4	5							
7727	1	1	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	5		
7728	1	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	5							
7729	1	1	1	1	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	9	4	4	4	5						
7730	1	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	5			
7731	1	1	1	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	5			
7732	1	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	5	
7733	1	1	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	5						

Appendix 3. Development stage of pups recorded on transects in 13 areas on Sable Island, one area from Hay and White Island. Data from White Island were not sufficient to estimate the distribution of births and therefore were not used.

Location	Date	Development Stage					Total
		1	2	3	4	5	
Sable East							
1. North Beach, East Light Cut	12/17/2009	28	40	1	0	0	69
	12/31/2009	1	128	14	0	0	143
	1/8/2010	1	67	35	6	1	110
	1/14/2010	0	17	72	38	13	140
	1/22/2010	0	4	17	30	64	115
2. North Beach, Long Dune	12/17/2009	27	49	2	0	0	78
	12/31/2009	4	136	26	1	0	167
	1/8/2010	7	28	61	16	5	117
	1/14/2010	1	27	28	50	37	143
	1/22/2010	0	5	19	15	91	130
3. South Beach, Lakeshore	12/17/2009	51	94	11	0	0	156
	12/31/2009	5	121	19	0	0	145
	1/8/2010	11	22	64	21	4	122
	1/14/2010	5	20	74	35	8	142
	1/22/2010	1	18	28	12	49	108
4. South Beach, No. 3	12/18/2009	25	55	0	0	0	80
	12/23/2009	34	64	32	0	0	130
	12/31/2009	2	130	0	0	0	132
	1/8/2010	5	18	61	33	15	132
	1/14/2010	5	13	61	46	18	143
	1/22/2010	1	4	48	48	51	152
5. South Beach, Tern Colony	12/22/2009	70	33	1	0	0	104
	12/31/2009	15	128	0	0	0	143
	1/8/2010	15	29	72	12	1	129
	1/14/2010	2	15	90	33	17	157
	1/22/2010	0	4	36	31	65	136
6. South Beach, Refrigerator	12/18/2009	22	60	9	0	0	91
	12/23/2009	24	58	36	0	0	118
	12/31/2009	0	95	27	12	0	134
	1/8/2010	6	19	61	34	6	126
	1/14/2010	1	26	13	18	72	130
	1/22/2010	2	6	17	24	91	140

Appendix 3. (Continued.)

Location	Date	Development Stage					Total
		1	2	3	4	5	
7. North Beach, Mobil	12/18/2009	18	56	2	0	0	76
	12/22/2009	34	32	20	0	0	86
	12/31/2009	3	131	2	0	0	136
	1/7/2010	7	38	68	4	1	118
	1/15/2010	1	20	115	28	3	167
	1/22/2010	2	6	17	24	91	140
8. North Beach, SOB	12/18/2009	12	66	6	0	0	84
	12/22/2009	26	54	28	1	0	109
	12/31/2009	2	124	4	1	0	131
	1/7/2010	10	18	48	21	10	107
	1/14/2010	0	19	39	52	48	158
	1/22/2010	0	5	25	17	57	104
Sable West							
9. North Bead, Dead Horse Pass	12/17/2009	9	32	3	0	0	44
	12/31/2009	14	59	75	1	0	149
	1/7/2010	11	43	82	25	1	162
	1/15/2010	5	16	100	31	20	172
	1/22/2010	0	6	92	38	77	213
10. North Beach, BIO House	12/17/2009	18	42	1	0	0	61
	12/31/2009	41	89	25	0	0	155
	1/7/2010	31	28	103	10	2	174
	1/15/2010	7	14	141	8	6	176
	1/22/2010	2	7	91	50	18	168
11. South Beach, West Spit	12/17/2009	24	41	0	0	0	65
	12/23/2009	44	35	5	0	0	84
	12/31/2009	14	62	80	1	0	157
	1/7/2010	10	17	121	14	1	163
	1/15/2010	5	17	99	35	39	195
	1/22/2010	1	11	42	48	89	191
12. North Beach, West Spit	12/17/2009	14	27	2	0	0	43
	12/31/2009	28	46	86	2	0	162
	1/7/2010	11	31	97	21	6	166
	1/15/2010	8	16	93	20	19	156
	1/22/2010	2	7	55	36	81	181

Appendix 3. (Continued.)

Location	Date	Development Stage					Total
		1	2	3	4	5	
13. South Beach, Dead Horse Pass	12/17/2009	23	39	7	0	0	69
	12/22/2009	41	38	10	0	0	89
	12/31/2009	11	65	73	0	0	149
	1/7/2010	11	13	135	16	0	175
	1/15/2010	3	14	102	50	10	179
	1/22/2010	3	6	43	36	101	189
Hay Island							
	16/01/2010	27	682	724	41	13	1,487
	29/01/2010	1	27	262	158	152	600
	30/01/2010	1	26	310	250	276	863
	04/02/2010	1	28	323	358	504	1,214
White Island							
	16/01/2010	0	8	21	1	1	31
	27/01/2010	1	8	38	2	0	49
	04/02/2010	0	1	14	2	0	17